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The change in magnetization as a result of applied uniaxial stress has been measured in nickel and cobalt. Both tensile and compressive stresses were applied up to 125 MPa. Magnetostriction and anhysteretic magnetization as a function of stress were also measured. The change in magnetization with stress depended on the applied stress and the displacement between the prevailing magnetization and anhysteretic. At the loop tips, nickel showed a +6 mT (compression) and −6 mT (tension) magnetization change while cobalt displayed a +15 mT (compression) and −15 mT (tension) magnetization change. At remanence, nickel decreased in magnetization by 45 mT under either sign of stress, while cobalt decreased by 20 mT also under either sign of stress. Magnetomechanical changes in magnetization near the loop tips were mostly reversible, while at remanence the magnetomechanical change was predominately irreversible. Cobalt generally displayed larger changes in magnetization with stress than nickel at locations close to the loop tips, while the converse was true at locations near remanence. The results confirm the hypothesis that the magnetomechanical effect ($dM/d\sigma$) depends on the displacement between the anhysteretic and prevailing magnetization. © *1997 American Institute of Physics.* [S0021-8979(97)39608-X]

INTRODUCTION

A magnetic material in which there is an induced anisotropy associated with magnetoelastic coupling will experience a change in magnetization with the application of stress. The change in magnetization with stress that occurs without changing the external magnetic field is called the magnetomechanical effect. The magnetization change occurs as a result of a change in the magnetoelastic energy of the system,[1] and this can be described in terms of an additional term to the effective magnetic field felt by the sample[2]

$$H_{\mathrm{eff}}=H_{\mathrm{appl}}+\alpha M+\left(\frac{3\sigma}{2\mu_0}\right)\left(\frac{d\lambda}{dM}\right), \tag{1}$$

where H_{appl} is the applied magnetic field, αM is the interaction field arising from the ordering of the moments, σ is the applied stress, μ_0 is the permeability of free space, λ is the magnetostriction, and M is the magnetization. Research on the magnetomechanical effect has usually focused on iron based materials.[3–6] In this study nickel and cobalt have been investigated. These materials have significantly different anisotropy coefficients and magnetostrictions from iron and therefore provide a useful test of the generality of the magnetomechanical theory developed previously.

MATERIALS

The materials in this study were 99.99% pure, annealed, polycrystalline nickel and cobalt. Samples were in the shape of cylindrical tensile specimens, 82 mm in length, suitable for both tension and compression tests. A magnetic field was applied to the samples by a solenoid surrounding the sample, collinear with the stress axis. Magnetic field was measured by a Hall effect sensor, magnetic flux was measured by a flux coil and strain was measured by a strain gauge. Stress was calculated from the strain by multiplication with the Young's modulus (210 GPa for Ni, 180 GPa for Co). The magnetomechanical effect was measured at nine locations along the upper branch of the hysteresis loop, from near-positive saturation to near-negative saturation. Each sample was cycled through two complete hysteresis loops before setting the magnetic field H at the desired level prior to measurement. For a magnetomechanical measurement, the magnetic field was held constant while stress was applied in a series of stress-release cycles of increasing amplitude. The change in magnetization was measured as a function of the stress.

RESULTS

The magnetostrictive responses of nickel and cobalt under different stress levels are shown in Figs. 1 and 2. The magnetostriction was measured through a complete hysteresis cycle, while the stress was held constant. There was some hysteresis in magnetostriction, although in the case of cobalt this was negligible. In nickel compression reduced the magnitude of magnetostriction while tension increased the magnitude of magnetostriction. Stress had less effect on the magnetostrictive behavior of cobalt because the magnetoelastic energy of cobalt at 125 MPa, $(3/2)\sigma\lambda=1.875\times10^3\ \mathrm{J\,m^{-3}}$, was well below the anisotropy energy of

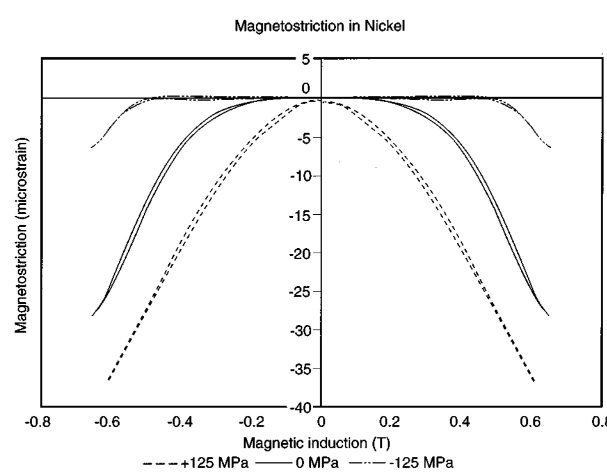

FIG. 1. Magnetostriction in nickel over a complete hysteresis cycle.

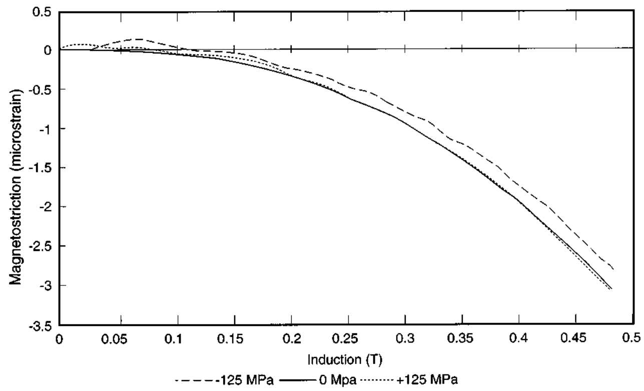

FIG. 2. Initial magnetostriction curves for cobalt.

4.1×10^5 J m^{-3}, and so did not significantly affect the domain structure, whereas in nickel the magnetoelastic energy was 6.5×10^3 J m^{-3} which is larger than the anisotropy energy of 4.5×10^3 J m^{-3}.

The magnetomechanical behavior of nickel starting from remanence is shown in Fig. 3. The sample was initially magnetized to near positive saturation and the applied magnetic field was then reduced to zero, leaving the sample at remanence. The magnetization decreased upon application of either tension or compression. Upon removal of the tension, the magnetization partially recovered, indicating that some of the initial decrease in magnetization was reversible. Upon removal of compression, the magnetization continued to decrease, indicating an almost completely irreversible change in the magnetization with stress. In addition, most of the change in magnetization upon re-application of the stress occurred after the maximum stress of the previous cycle was exceeded.

The magnetomechanical behavior of cobalt starting from remanence is shown in Fig. 4. As with nickel, the magnetization decreased upon the application of tension or compression. In cobalt, the magnetization change upon removal of stress differed from that in nickel. Specifically, the magnetization upon removal of stress, for either tension or compression showed little reversible recovery of magnetization.

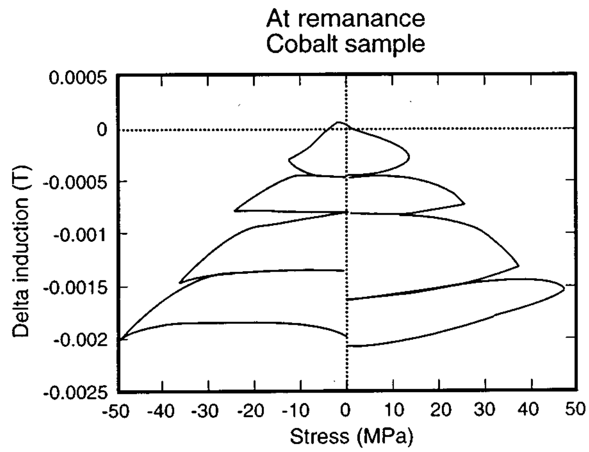

FIG. 4. Magnetomechanical behavior in cobalt at remanence.

The magnetomechanical behavior was different at locations on the curve away from remanence as shown in Figs. 5 and 6. In nickel, at a magnetization below remanence, the application of tension reversibly increased the magnetization while the application of compression reversibly reduced the magnetization. In cobalt, also at a magnetization level below remanence, the application of either tension or compression irreversibly reduced the magnetization.

DISCUSSION

It has been suggested previously that a factor which determines the direction and magnitude of the change in magnetization with stress is the displacement between the prevailing hysteretic magnetization and the anhysteretic magnetization When the hysteretic magnetization is above the anhysteretic, the free energy of the system is reduced by a reduction of magnetization. Therefore, application of stress in the form of cyclic stress, reduces magnetization The larger the displacement between hysteretic and anhysteretic magnetization, the larger the magnitude of $dM/d\sigma$. This can be seen by comparing Figs. 3 and 4, nickel decreased its induc-

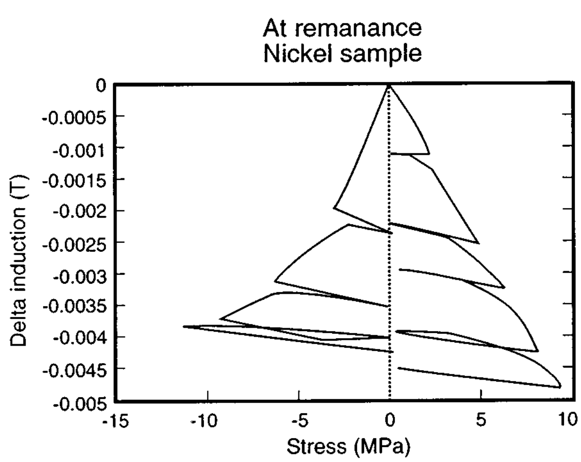

FIG. 3. Magnetomechanical behavior in nickel at remanence.

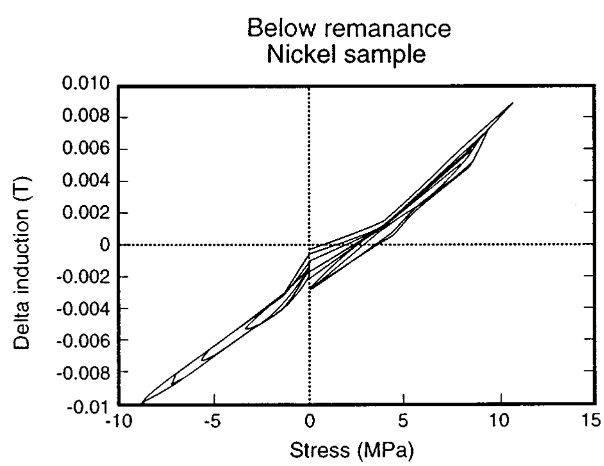

FIG. 5. Magnetomechanical behavior in nickel at a magnetization level below remanence.

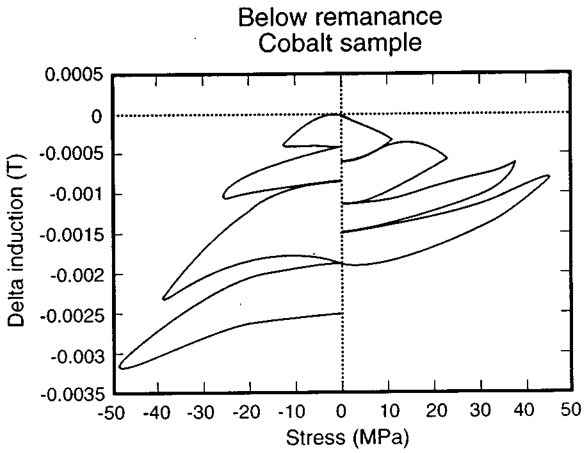

FIG. 6. Magnetomechanical behavior in cobalt at a magnetization level below remanence.

tion from its remanent value of 0.25 T by 4.2 mT, while cobalt decreased from its remanent value of 0.11 T by 2 mT.

The sign on the product of $\sigma(d\lambda/dM)$ determines the direction of the stress contribution to the effective magnetic field. For locations on the upper branch of the hysteresis loop in the third quadrant of the MH plane used for Figs. 5 and 6, $(d\lambda/dM)$ was positive for both Ni and Co. This arose because the magnetization was negative and further negative changes in M gave rise to negative changes in λ. Consequently in nickel tensile stress combined with positive $(d\lambda/dM)$ to give a positive contribution to the effective field which increased the anhysteretic magnetization (i.e., displaced it to less negative values) and resulted in the positive change in magnetization under tension observed in Fig. 5. Conversely the compressive stress decreased the anhysteretic magnetization (i.e., displaced it to more negative values) and so led to the observed decrease in magnetization under compression. In cobalt, the effective field acting on the magnetization was small because $\sigma(d\lambda/dM)$ was small. Therefore, it did not affect the magnetization as significantly as in nickel, and the main effect observed was then simply a change in magnetization towards the anhysteretic.

CONCLUSIONS

The magnetomechanical responses of 99.99% pure nickel and cobalt have been presented. Large irreversible changes in magnetization were found to occur when the samples were initially at remanence, while there was a mixture of reversible and irreversible behavior at locations away from remanence. At the loop tips the behavior was mostly reversible. The magnetization change with stress depended on the combination of the displacement between anhysteretic and prevailing magnetizations and the effective magnetic field produced by stress. The magnetization tended toward the anhysteretic upon application of stress, regardless of the sign of the stress.

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